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TITLE: **Studying Upper-Limb Amputee Prosthesis Use to Inform Device Design**

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The proposed project investigates the nature of upper limb prosthesis use in everyday tasks through in-home and lab-based studies on upper-limb amputees and matched unimpaired subjects.
During the second year we recruited amputee participants and completed several at-home portions of the study. A study of the resulting videos led to a new prosthetics-use taxonomy that is generalizable to various levels of amputation and terminal devices. The taxonomy was applied to classification of the recorded videos via custom tagging software with midi controller interface. The software creates Matlab-readable log files. Motion capture development of a body compensation experiment and kinematics based metric were also made.
In the next year recruitment of amputee and able bodied participants will continue in an effort to complete more studies and generate data for analysis.

15. SUBJECT TERMS
Upper Limb Prosthetics, Amputee, Assistive Technology, Motion Capture

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1. INTRODUCTION

The proposed project centers on investigating the nature of upper limb prosthesis use in everyday tasks through both an in-home and lab-based study on upper-limb amputees and age and gender-matched normal subjects. For the in-home study we will use an unobtrusive head-mounted camera to record and then later observe prosthesis/hand use during domestic tasks. In the lab study we will use a motion capture studio and video cameras to record accurate and detailed upper body motion during a series of standardized tasks. These tasks are clinically validated measures of hand / arm function functional evaluation. By recording participant performance and examining prosthesis/hand use, we expect to identify shortcomings in current prosthetic terminal devices and implementations that will inform improvements to existing designs and inspire new classes of devices in the future.

2. KEYWORDS

Upper Limb Prosthetics, Amputee, Assistive Technology, Motion Capture

3. ACCOMPLISHMENTS

This reporting period covers the third year of the project. This portion of the project has focused on video data acquisition and analysis.

What were the major goals of the project?

The major goals of this project were observing the upper limb manipulation techniques used by numerous upper limb prosthesis wearers and 'healthy' individuals (i.e. those with intact upper limbs) when achieving a variety of tasks in unstructured (in their own home) and structured (in the lab) environments. Comparing data from these demographics over the different tasks and environment we aim to determine differences in manipulation techniques between prosthesis wearers and the healthy 'baseline'. In particular we wish to identify the shortcomings of particular prosthetic devices or setups while looking for methods employed by prosthesis users to overcome these limitations.

Originally the study proposed the use only of head-mounted cameras for observation. This was extended to include a motion capture system capable of accurately recording upper body motion to provide much richer movement data. The motion capture setup will be used only in the laboratory setup, due to the complexity of the measurement equipment and relatively limited capture volume.

What was accomplished under these goals?

In the **first year** we prepared measurement equipment and the necessary protocols to enter participants into our study. In particular the following achievements were made:

1. Experimental protocols were finalized

2. The protocol was approved by IRBs for all institutions and the DoD. Necessary human subjects training was also completed for relevant members of the study team.

3. The head-mounted camera setup has been established (a GoPro Hero 3+, modified to accept an external pocket sized battery – giving 6 hours of recording time instead of 30 minutes with the internal battery).

4. Software to aid analysis of the head-mounted camera data was prototyped

5. A Vicon optical motion capture system was selected (after reviewing several options), purchased and installed in the laboratory space of Yale University

6. Extensive familiarization with the Vicon system was completed. This began with on-site training from a Vicon representative but since then has led to the following:

    a. Optimized camera placement (13 cameras in a 5x5m space) for bi-manual upper body capture when standing or seated. This also involved installing mounting rails in the laboratory

    b. Optimized marker placement for robustness to marker occlusions (when motion capture markers are hidden from view in particular body poses). This includes flexible, wearable marker clusters and custom software methods to reconstruct occluded markers.

    c. Custom data processing scripts to extend the functionality of Vicon software to export skeletal angles. These scripts have been written to match the guidelines of the international society of biomechanics (ISB)

7. Collection and setup of materials for the laboratory space. This includes a variable height desk (to simulate a kitchen counter or work desk) and various household items.

The setup of equipment took longer than initially suggested in the original proposal. This was due to the inclusion of the motion capture system. This system required development of specific skills and significant trial and error regarding camera placement, focusing and marker sets.

In the **second year** of the project the following further development were made:

1. A pilot study was completed of the at-home study with a healthy non-amputee volunteer. This highlighted problems with reliability of the GoPro remote control and particular brands of memory card.

2. Amputee participant recruitment began, with various advertisements placed in specialist online forums and social media sites.

3. Three amputee participants were recruited within Connecticut and New York. Two were congenital transradial amputees (one male, one female, both body powered users) and

one was a non-congenital shoulder disarticulation amputee (who uses a myoelectric prosthesis)

4. Custom video analysis software was completed, allowing quick and robust video tagging by use of a midi controller. Exported log files may be read by Matlab or Excel.

5. An initial 'prosthesis use taxonomy' was created, based on observation of the video, to allow structured recording and categorization of manipulation events observed in the recorded videos.

6. The recruited amputees all took part in the at-home study.

    a. Several hours of video data were generated for each participant

    b. A number of participant videos were de-identified via blurring of portions of the video

    c. Initial video tagging was completed by use of the custom software. A summer intern was hired and trained for this task. He will continue to work with us in his spare time for the remainder of the project.

    d. Initial trends were observed in video tagging log files, via Matlab analysis.

7. Further preparations were made for Motion Capture analysis, including a full pilot study with members of the lab

    a. An additional body compensation analysis was planned and piloted on members of the laboratory

In the **<u>third year</u>** of the project the methods previously developed were refined, permitting analysis of the video data (which continues to be acquired) and leading to initial publication/dissemination. More specifically:

1. The prosthesis-use taxonomy was refined as finalized, as shown in Figure 1.

2. Improvements were made to the tagging and analysis software, removing bugs and increasing robustness.

3. 23-minutes of video data for the first three participants (whose data was collected in year 2) was processed using the video tagging software. This involved the identification of over 2,300 manipulation instances. Among other results, it was noted that the body powered of the transradial participants was used more in non-prehensile manipulation than in prehensile grasping.

4. The findings were accepted as a full paper with poster presentation at the IEEE International Conference on Rehabilitation Robotics (ICORR) in London, UK.

5. The findings were also accepted and presented as an abstract/podium presentation at the Myoelectric Control Symposium (MEC17), in Frederiction, New Brunswick, Canada.

6. Following limited amputee participant recruitment success over the first 2 years of the project, a paid Facebook advertisement and custom Facebook page were created to attempt recruitment by social media. This led to recruitment of one transradial amputee, who was visited in person by a member of the study team and completed the study.
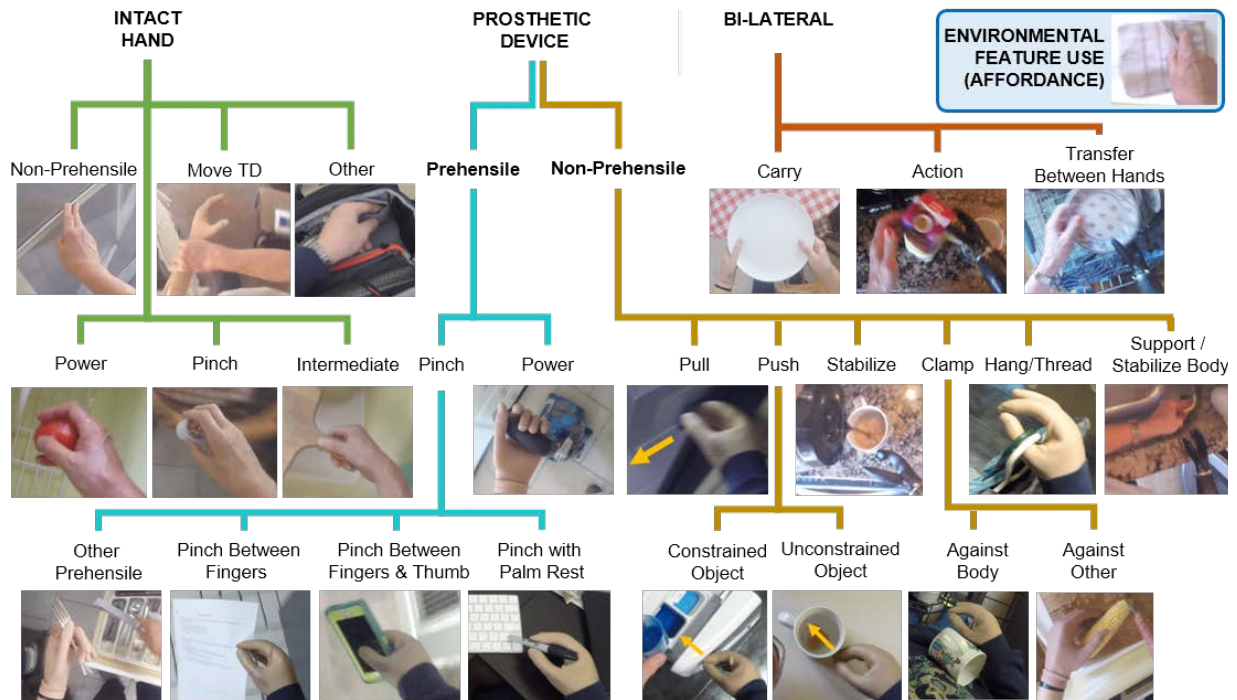
Figure 1: The fully developed prosthesis-use taxonomy

7. After all options for local amputee participant recruitment (within ~150 miles of New Haven) had been exhausted, we modified our approach to enable amputees to take part in the study remotely, by receiving the camera kit and instructions via courier mail. This enabled us to recruit 5 more amputee individuals from across the US.

8. Three of the 'mail-out' participants have completed or partially completed the GoPro study so far.

9. An undergraduate student was hired to perform video tagging on the project during the spring semester. Another was hired to perform video tagging full time over the summer and after her success at this has been kept on as a part-time video tagger during the school year. A grad student has also begun contributing to video tagging. This additional manpower has greatly increased data analysis output compared to when only a research scientist was completing the tagging (as was the case for the original 23 minutes of analysis).

10. Over 8 hours of data has now been analyzed for the seven amputee participants who have contributed data thus far. Some of these participants made use of more than one terminal device (Figure 2). This analysis involved the manual identification of over 15,000 manipulation tags. Initial proportional breakdown of this data into manipulation categories is shown in Figure 3.

11. A grad student in the Grab Lab has begun specifically investigating Within-Hand-Manipulation (WIHM) activities in the recorded videos, this is a largely unexplored aspect of human manipulation.

12. A different grad student in the Grab Lab has begun specifically investigating environmental affordance use in the recorded videos in order to better define the
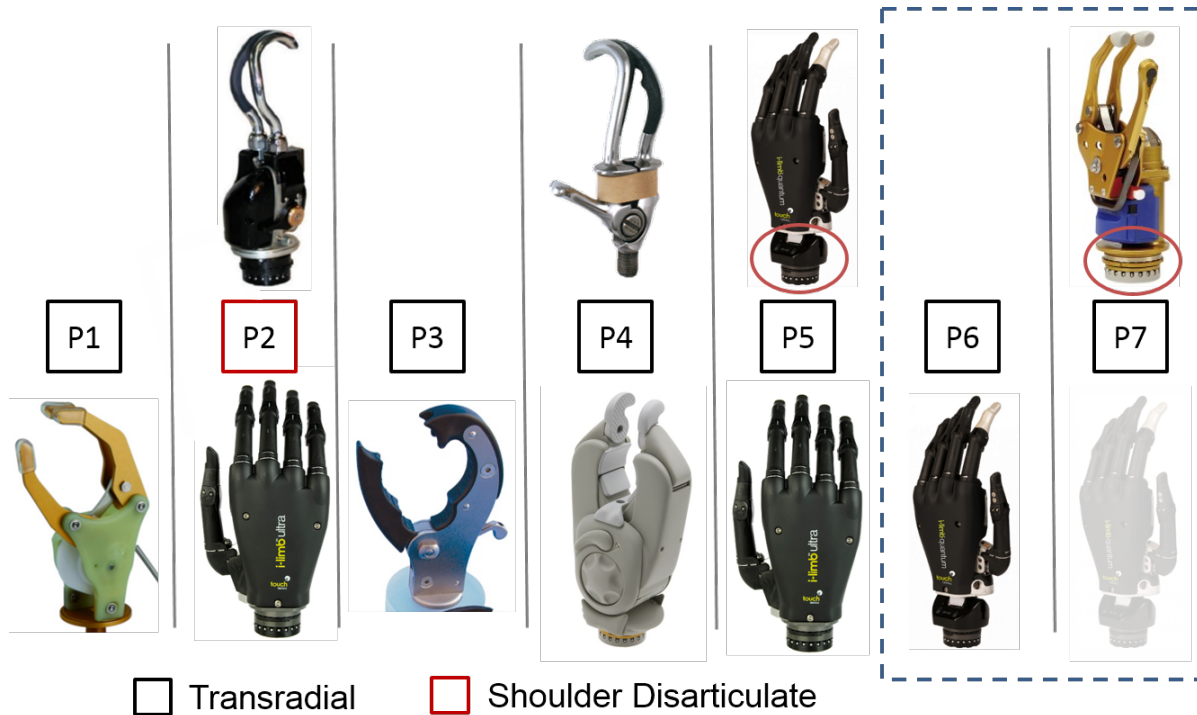
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Figure 2: Video data has been collected from 7 participants to date, some of whom have used multiple terminal devices during the video recording (P7 did not record enough data with their multi-grasp hand to allow analysis).

affordance manipulation tag to deal with current uncertainty about classification. There is little existing literature on this area.

13. An advertisement recruiting able-bodied participants was posted on the local craigslist. Potential participants who passed screening had their details entered into a local database for gender / age / height matching to amputee participants. Matching participants will be enrolled once data collection has been completed for amputee participants.

14. Pilot studies have been completed with the motion capture system, using non-amputee participants.

15. Following positive reception of work presented at ICORR, Dr. Spiers was invited to provide a keynote presentation on this project at the next Trent International Prosthetics Symposium (TIPS 2019, UK)

What opportunities for training and professional development has the project provided?

The project provided the opportunity for familiarization with literature on prosthetics, motion capture and functional outcome measures. Attendance at the MEC (Myoelectric Controls Symposium, New Brunswick Canada) and ICORR (IEEE International Conference on Rehabilitation Robotics) conferences have greatly contributed to familiarization with the field of upper limb prosthetics.

Technical training was completed by Dr Adam Spiers on the Vicon motion capture system. Training was also completed by Dr. Spiers on protocols and policies regarding human

experiments. Dr. Spiers has subsequently trained two grad students in how to use the motion capture system and written a guide for use in the lab.

As a result of the at-home studies, Dr. Spiers has become familiar with running studies in non-
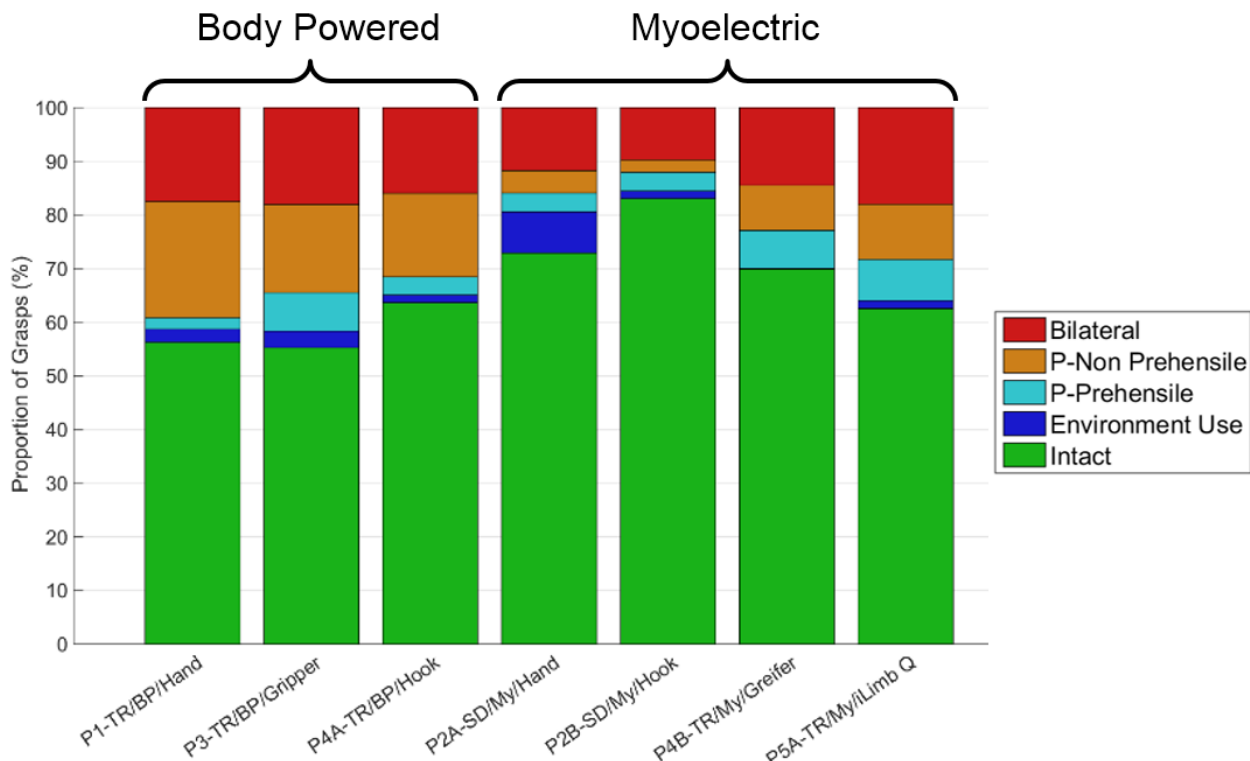

Figure 3: Over an hours of data has been analyzed for a variety of terminal device uses, across 5 different participants. The above figure shows proportion of manipulation strategy.

laboratory scenarios.

Two undergraduate students and two graduate students have been trained in video tagging and identifying manipulation activities.

How were the results disseminated to communities of interest?

Internal dissemination of findings have been presented to our lab.

A regular paper was accepted for ICORR 2017 (IEEE International Conference on Rehabilitation Robotics) and a poster presentation given at the event.

An abstract was accepted for MEC 2017 (Myoelectrics Control Symposium) and a podium presentation given at the event.

What do you plan to do during the next reporting period to accomplish the goals?

In the next period we plan the following

1. Complete recruitment and data collection for amputee participants. In particular we hope to recruit at least one trans-humeral amputee, as this level of impairment is currently absent from our data set.

2. Recruit gender, age and height matched <u>non-amputee</u> participants for completion of home studies.

3. Continue tagging of existing at-home video data using the custom video tagging software

4. Begin in-lab motion capture studies with able-bodied and amputee participants

5. Process resulting Vicon motion capture data

IMPACT

What was the impact on the development of the principal discipline(s) of the project?

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

The manipulation taxonomy developed for this work fills a gap in prosthetics terminology that we assume will be used by other researchers in the future. Such manipulation taxonomies (e.g. the Feix taxonomy) are widely used in healthy human and robotic hand analysis, yet no such tool exists for prosthetics use. Though Belter et al created a 'split hook' taxonomy, this was not applicable to other terminal devices, such as multi-finger hands. We have designed the taxonomy to be generic and applicable to all upper limb prosthetic systems and levels of amputation.

Similarly, we believe the body compensation measure under development for this project will also provide a tool that may be useful for motion analysis in research, and possibly clinical setting. Despite body compensation being a known, unwanted factor of motion impairment, there is no universal method of quantifying the level of compensation for particular motions. This is addressed by our kinematics based algorithm, which may be easily added to a motion capture analysis.

What was the impact on other disciplines?

Nothing to report

What was the impact on technology transfer?

Nothing to report

What was the impact on society beyond science and technology?

Nothing to report

5. CHANGES/PROBLEMS:

Changes in approach and reasons for change

Addition of motion capture to the in-lab portion of the proposed study.

Modification of experiment protocol to enable GoPro cameras to be mailed to participants, rather than an experimenter visiting them in person. This has enabled persons to be recruited from outside of the local area.

Actual or anticipated problems or delays and actions or plans to resolve them

Year 1 - Training, setup and familiarization of with the motion capture system added delays to the project compared to the original forecast. However we believe the quality and impact of the resulting data will be much higher as a result of this new measurement tool and the time taken to learn how to use it.

Year 2 – Difficulties in participant recruitment delayed the start of the at-home study and has slowed down project progress. Typical channels of subject recruitment (online advertisements) did not generate any participants. Instead personal connections through team members and/or their colleagues led to subject recruitment in all cases.

Year 3 – Amputee participant recruitment continued to be a source of problems in the first half of the year. This was alleviated by enabling the study equipment to be mailed out to participants across the US. Video tagging also took longer than anticipated (up to 2 hours of processing time for a minute of video), this was aided by assigning undergraduate and graduate students to video tagging roles.

Changes that had a significant impact on expenditures

Nothing to report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to report

6. PRODUCTS:

Publications, conference papers, and presentations

Spiers, A. J., Resnik, L., & Dollar, A. M. (2017, July). Analyzing at-home prosthesis use in unilateral upper-limb amputees to inform treatment & device design. In *Rehabilitation Robotics (ICORR), 2017 International Conference on* (pp. 1273-1280). IEEE.

Spiers, A. J., Resnik, L., & Dollar, A. M. (2017, August). Classifying and Quantifying Unilateral Prosthesis Use in Home Environments to Inform Device and Treatment Design. *Myoelectric Control Symposium, (MEC)*

Website(s) or other Internet site(s)

Recruitment Page

Technologies or techniques

Motion capture marker sets and processing techniques associated have been developed. These will accompany future publications as appendices.

The Midi controller based video tagging software developed for this project is robust and easily scalable. We are considering open-sourcing the code afterwards for use by other researchers.

The prosthetics use taxonomy is a manipulation classification technique that will be applicable to general analysis of upper limb prosthesis use.

The body compensation algorithm will be published with accompanying data, following completion of the in-lab study.

Inventions, patent applications, and/or licenses

Nothing to report

Other Products

Nothing to report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Name:	Aaron Dollar
Project Role:	PI
Researcher Identifier (e.g. ORCID ID):	Aaron.dollar@yale.edu
Nearest person month worked:	1
Contribution to Project:	**Expert on human hand functional use and robot / prosthetic hand development. Contributed to Protocol development, measurement equipment selection and setup.**
Funding Support:	This award.

Name:	Linda Resnik
Project Role:	Co-PI
Researcher Identifier (e.g. ORCID ID):	linda_resnik@brown.edu
Nearest person month worked:	1.2
Contribution to Project:	**Expert on upper limb prosthetics and measures of upper limb functionality and rehabilitation outcomes. Contributed to protocol development.**
Funding Support:	This award

Name:	Adam Spiers
Project Role:	Postdoctoral Associate
Researcher Identifier (e.g. ORCID ID):	adam.spiers@yale.edu
Nearest person month worked:	12
Contribution to Project:	**Postdoc researcher responsible for running at-home and in-lab studies. Contributed to protocol development, IRB submission (Yale only), equipment selection, setup, customization and familiarization.**
Funding Support:	This award.

Name:	Kate Barnabe
Project Role:	Administrative Lead
Researcher Identifier (e.g. ORCID ID):	Kate.Barnabe@va.gov
Nearest person month worked:	1.2
Contribution to Project:	**Protocol development.** **IRB submissions** **(all institutions and DOD).** **Project administration.**
Funding Support:	This award

Name:	Karli Cecil
Project Role:	Undergraduate Intern
Researcher Identifier (e.g. ORCID ID):	Karli.Cecil@yale.edu
Nearest person month worked:	4
Contribution to Project:	**Video Tagging**
Funding Support:	This award

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to report

What other organizations were involved as partners?

Nothing to report

8. SPECIAL REPORTING REQUIREMENTS

A Quad Chart accompanies this report

9. APPENDICIES

None

Studying Upper-Limb Amputee Prosthesis Use to Inform Device Design

Log# 13116005, Award# W81XWH1410277

**PI:** Aaron M. Dollar   **Org:** Yale University   **Award Amount:** $476,646

Study/Product Aim(s)

• Investigate prosthesis use during daily living by upper-limb amputees
• Develop task-related prosthesis usage/non-usage statistics
• Examine compensatory motions/actions
• Identify areas for device improvement and opportunities for assistive technologies

Approach

The upper-limb usage of amputee and age/gender-matched unimpaired subjects will be examined in both their home environments and a fixed laboratory environment doing a pre-described set of activities of daily living (ADLs). Their actions/movements will be recorded with head-mounted cameras (home) and motion-tracking equipment (lab).
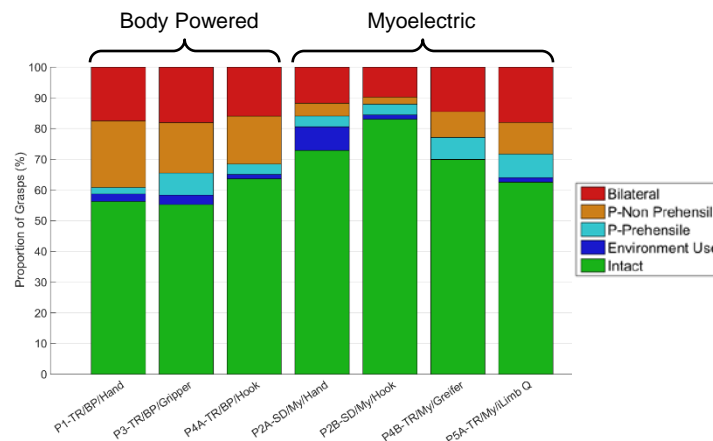
Over an hour of participant video data has now been analyzed, resulting in over 15K manipulation tags. This involves 5 participants in 7 conditions. Data from another 2 participants is currently under analysis.

Timeline and Cost

Activities	Milestone (m)	CY 14 Q 1	2	3	4	15 5	6	7	8	16 9	10	11	17 12
Protocol Develop	IRB Approvals			m									
Study Equipment	Fab complete			m									
Recruit Subjects	Enrollment complete								m				
Home-based video study	Completion								m				
Lab-based study	Completion								m				
Data analysis	Final Publication												m
Estimated Budget ($K)		**$25.6**				**$247**				**$95.4**			**$108.6**

Updated: (10/5/17)

Goals/Milestones

✓ Protocol Development and IRB submissions (months 1-12)
✓ Fabricate and Test study equipment (months 1-12)
○ Subject Recruitment (months 12-24)
○ Home-based video study of ADL tasks (months 12-24)
○ Lab-based video study of ADL tasks (months 12-24)
○ Prepare and Analyze task performance data (months 15-36)
('○' Denotes task in progress)

Comments/Challenges/Issues/Concerns

• Re-budgeted to allow purchase of motion-tracking equipment
• In-home study and video tagging / data analysis is in progress
• Amputee recruitment proving more difficult than anticipated
• No-cost extension was requested to enable the motion-capture study and further analysis

Budget Expenditure to Date
Projected Expenditure: $475,000
Actual Expenditure: $450,000